Stream Mapping in Maryland

…finding first order Piedmont channels

(A Background Literature Review)

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Table of Contents

1. Introduction

Within Maryland alone, there are estimated to be 14 to 17 thousand miles of stream channels (MDNR, unpublished data). Knowing the location of channel drainage networks in the landscape is vital for environmental planning and management efforts. Federal, state, and local government agencies rely on maps of stream channel networks for surveys of aquatic habitat, assessments of non-point source loadings of pollutants to the Chesapeake Bay, and general land use planning activities. While large channels associated with rivers are most widely recognized in the landscape, the majority of the total drainage network lengths are occupied by small headwater channels. Despite their abundance in the landscape, they are the least well mapped. As indicated by the statewide estimate of total stream miles, there may be several thousand miles of stream channels that are missing from spatial databases. Most, if not all, of the missing channels are located at the uppermost end of the drainage networks. The mapping deficiencies are attributed to inaccurate determinations of the upper channel network limits. Accordingly, this paper is intended to provide background information on stream channel mapping with a focus on first order channels that are poorly delineated within the landscape. Approaches that can be used to identify the uppermost limits of first order channels and comprehensively develop improved stream maps are also provided.

2. Mapping Techniques

Stream drainage networks are most widely recognized as components of topographic maps that have been published by the United States Geological Survey (USGS) since the 19th century. Techniques used to develop the original maps were based on measurements conducted at a scale incapable of accurately showing small channels. Drainage networks were commonly added as map attributes using general field observations. These were later improved through the use of aerial photographs that enabled more extensive documentation of the presence of water-bodies in the landscape. Recent standards for the revision of 1:24,000 scale quadrangle maps published by the USGS indicate that updates to the maps continue using aerial photography. However, not all photo-revisions are field checked or "confidently" positioned (USGS, 1996). Those that are confidently positioned within 40 feet at 1:24,000 are considered "definite", whereas those that are not confidently positioned are considered "indefinite" (USGS, 2003). Published mapping standards specify that "if the headwaters of a stream/river are closer than 1000 feet at 1:24,000 scale from a saddle or divide, the stream/river should be shown starting 1000 feet from the saddle or divide. Standards for the National Hydrography Dataset are less detailed, stating that the upper limit of a stream/river is where the feature becomes evident as a channel (USGS, 1999a). The classifications of small channels as intermittent or perennial have been acknowledged by the USGS to be a "subjective process" that does not involve scientific measurements (USGS, 2001). In addition to being vaguely defined, the past approaches for developing or enhancing stream maps have not been extensively integrated with field measurements. This has limited the ability to quantify uncertainty associated with stream measurements using the stream data layers.

With the advent of digital geographic information systems (GIS), the efforts to improve existing stream maps have received greater involvement from local and state government agencies. Criteria used for the development of the stream layers often focuses on the upslope expansion of the existing drainage network delineations on digitized USGS quadrangle maps through the use of high-resolution aerial photos. Stream layers that have been developed by the USGS and expanded by state and local government agencies in Maryland can be readily viewed on the Merlin GIS system at www.mdmerlin.net. The accuracy of the enhanced stream channel delineations available on line is limited by the resolution of the aerial photography. However, field-verification of the existing drainage network delineations has not been documented (Weber, 2003). Upgraded approaches are needed to develop well-defined stream delineations in Maryland.

3. Drainage Network Analyses

"Morphometry" can be generally defined as the measurement and analysis of landscape features (Bloom, 1991; Bates and Jackson, 1984). In 1945, Horton published a summary of morphometric analyses used in the investigation of stream drainage networks. The concept of designating stream *orders*, the classification of the relative position of streams within a drainage network, was presented as a primary basis for quantifying the physical properties of channel networks and formulating related "laws" (Smith, et. al., 2003). A related "law of stream *numbers*" was developed, stating that the relation between the number of stream segments of each order form an inverse geometric sequence with stream order number. That is, a linear relation with a negative slope develops from a plot of the number of stream segments (y-axis) using a logarithmic scale versus stream order (x-axis) (Leopold, et. al., 1964). Plotting the sum of the *lengths* associated with the segments of each stream order on logarithmic scale (y-axis) versus stream order (x-axis) results in a linear relation with a positive slope. This provides the basis for the "law of stream lengths" (Leopold, et. al., 1964).

The use of stream ordering provides the underlying basis for quantifying attributes identified by Horton as being necessary to describe a drainage network, including:

a) watershed drainage area,
b) bifurcation ratio (defined as the ratio of the number of stream channels of a given order to the number of stream channels of the next highest order),
c) stream length ratio (defined as the length of stream of a given order to that of streams of the next order), and
d) the mainstem length.

The average length of first order streams was also identified as being preferable to the mainstem length for the characterization of a network. However, this length is the most difficult to derive without extensive field surveys. Inaccurate estimates of first order channel numbers and lengths also can result in errors in the latter three attributes listed above.

The concept of drainage density, defined by equation 1, was presented by Horton as a metric to describe the degree of drainage development in response to climatic and physiographic factors. The fact that the average distance between stream channels is approximately equal to one half the reciprocal of the drainage density was then used for the development of a predictive relation for the length of overland flow on hillslopes (equation 2). Within the Mid-Atlantic, drainage networks with relatively high densities can be observed in mountainous areas, such as the Appalachian, Ridge and Valley, and Blue Ridge physiographic provinces. In contrast, low drainage densities occur in areas of low relief, such as the Coastal Plain on the Delmarva Peninsula.

1. $D_d = \sum L / A$

where D_d = drainage density, L = total length of stream channels, A = drainage area

2. $l_0 = 1/(2D_d)$

where l_0 = length of overland flow

Abrahams (1984) pointed out that control the density of channel networks vary with the scale of investigation and geomorphic processes governing channel initiation. At a macro-scale, Abrahams referenced work relating drainage density to precipitation, as well as an index of climate and vegetation developed by Chorley (1957), expressed as PE/P_MP_I (where PE is a vegetation-dependent precipitation index, P_M is the annual precipitation, and P_I is rainfall intensity). At a meso-scale, dominant influences included lithology, relief, and stage of drainage network development. Finally, micro-scale influences on drainage networks were identified as being related to space-filling, such as the location of the basin's outlet within the larger channel network and location of the basin head relative to the major network divide.

The factors operating at a micro-scale relate to a question regarding overland flow path lengths that Horton (1945) considered as an element contributing to the drainage network morphometry. Horton's model describing the evolution of drainage networks was partly based on a critical distance traversed by overland flow on a hillslope. Two flaws with the model have since been proposed (Leopold, et. al., 1964). First, micro-piracy of small channels (capture of a small channel by a larger one) is unlikely to be the cause of full integration of large-scale landscapes. Second, it is inconceivable that an area could provide a "clean slate" for the development of a drainage network. Head-ward growth models were subsequently proposed as an alternative explanation for drainage network evolution. In related studies, Schumm (1977) observed that drainage network development through head-ward growth continues through erosion processes until late in the adjustment cycle, even after stability has developed in other locations within the network. Collectively, the “critical distance” and “head-ward growth” concepts provided partial treatment of the processes influencing the morphometry of drainage networks. However, direct disturbances from urban and agricultural land uses may have over-riding influence on drainage network characteristics over short time scales.

4. Channel Landform Features

The differentiation of hillslopes from stream channels in a landscape can seem like a relatively straight-forward task because most individuals that spend time walking through natural areas have a vision (prototype) in mind of what each landform feature looks like. However, the vision usually includes sloping land with a relatively smooth surface near the uppermost ridge of a watershed (***fig. 1***) and large alluvial channels nested within well-developed lowland valleys (***fig. 2***). The conundrum arises from the fact that the transition between these two landform features is often complicated by the presence of relatively small intermediate features that are difficult to delineate.

Research on the geomorphology of headwater channels has been conducted in areas with steep relief (Hack and Goodlett, 1960; Istanbulluoglu, et. al., 2003; Whiting, et. al., 1999). However, the intermediate geomorphic features associated with the transition from hill-slopes to alluvial valleys need further attention in temperate humid settings, such as that of Maryland. In particular, more information is needed to properly characterize how, when, and where transitional features occur in areas of moderate relief, such as the dissected landscape of the Mid-Atlantic Piedmont physiographic province (Gomi, et. al., 2002).

Figure 1: Hilltops in Maryland's dissected Piedmont landscape. Source: MDDNR

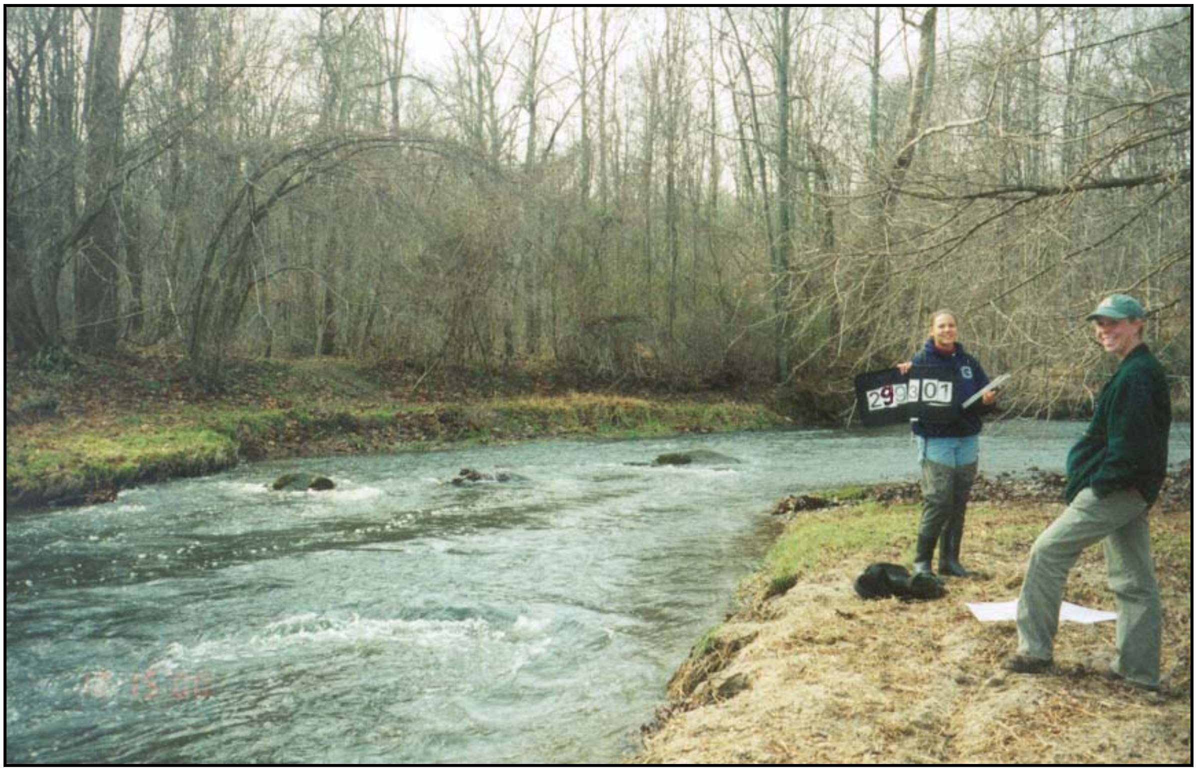


Figure 2: Alluvial channel and adjacent floodplain within a reach of the Middle Patuxent River in Maryland's Piedmont. Source: MDDNR.

Precipitation runoff traverses the landscape from the ridge top to alluvial channels, generating sediment from erosion along its path. The complexity and relative significance of the erosion patterns that can occur along the flow path underscores the importance of characterizing the transition from unchannelized hillslopes to alluvial valleys. Hydrologists have developed terms to define distinct surface runoff modes in headwater areas for the purpose of mathematical modeling. These modes have included *sheet flow*, *shallow concentrated flow*, and *channelized flow* (***fig. 3***; USDA, 1976). In the model, the path length of each runoff occurring in each mode is usually approximated, followed by independent computation of the related hydraulic conditions (flow velocity and "time of concentration"). This partitioning enhances the ability to predict hydrologic conditions within a watershed. From a physical process perspective, it is important to distinguish between the upper limit of a stream during rainfall runoff and a stream channel that is observable at all times. The upper limit of a stream, which is coincident with the upper limit of shallow concentrated flow, is not the same as the upper limit of a permanent stream channel that is able to be distinguished in the landscape during in dry conditions (Dietrich and Dunne, 1993). The identification of the physical features that mark the transition from shallow concentrated flows to channelized flow is important to address questions regarding watershed erosion processes for the development of accurate stream channel drainage network maps.

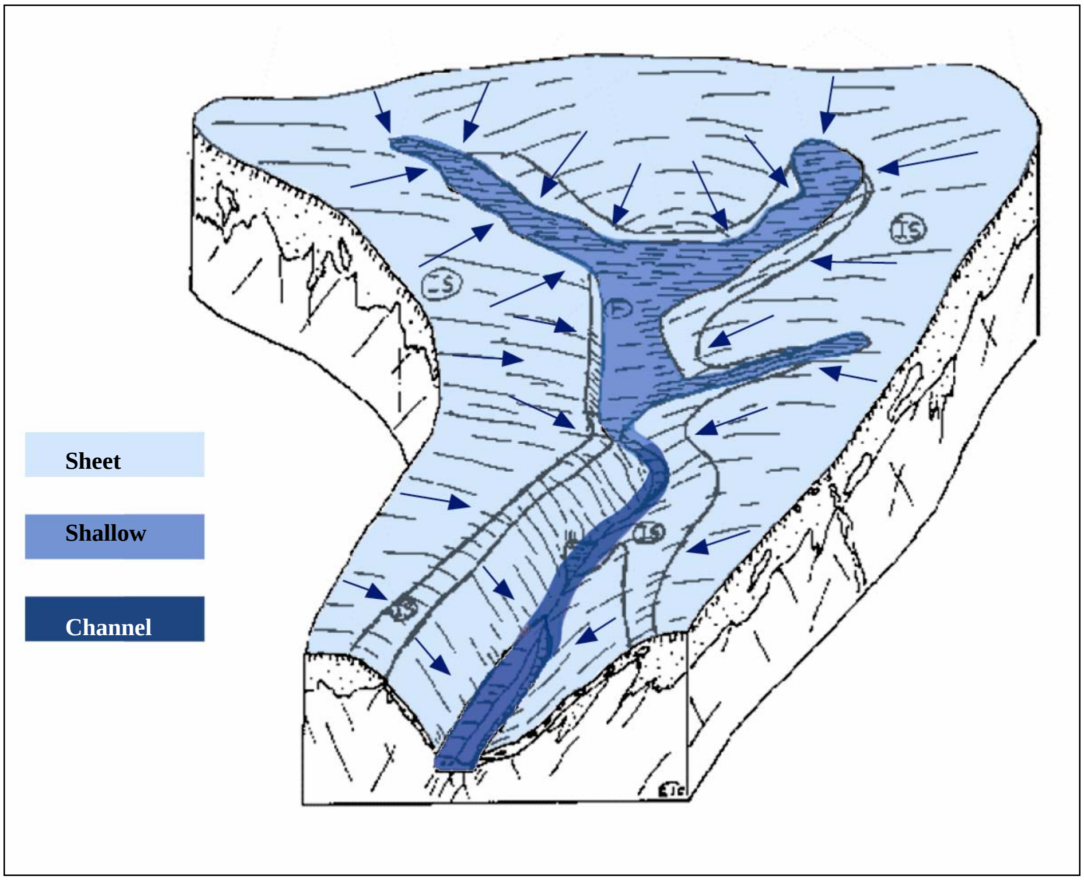


Figure 3: Surface runoff modes (sheet flow, shallow concentrated flow, and channel flow) used in USDA watershed runoff simulations (USDA, 1986). Source: Smith, et. al., 2003.

In Piedmont areas characterized by moderate hill-slope gradients averaging 0.075 m/m (Herrmann, 2005) a more detailed characterization of the intermediate landforms conveying sheet flows to alluvial valleys will include *swale*, *rill*, and *gully* channel features. Swales are slight depressions that are often swampy and convey concentrated flows during periods of runoff (Bates and Jackson, 1984). Rills were defined by Ritter (1982) as a set of well-defined sub-parallel channels in fine-grained soils that are no more than several centimeters wide and deep (***fig. 4***). Schumm (1956) further characterized rills on badland slopes as ephemeral features that could not be differentiated from permanent channels on the basis of width. Ritter's description clarified that heaving and other physical processes obliterate rill channels between periods of rainfall, which allows new channels to form in an entirely different location, thereby ensuring less than equal lowering of the entire slope surface. Downstream from rills, gullies have been described as permanent channels with cut banks and a steep head formed as a result of fluvial incision and surface erosion processes (Betts, et. al., 2003; Bloom, 1991) (*fig. 5*). *Alluvial* channels form further downstream, differing from gullies in that they are lined with materials carried by sediment from upstream channel reaches.


Figure 4: Rills observed in Piedmont farm fields. Source: MDDNR.

Figure 5: Eroded gully channel in the headwaters of the Middle Patuxent River in Maryland's Piedmont. Source: MDDNR.

The geomorphic characteristic landforms of channels have been investigated by a number of authors for the purpose of describing their erosion processes, sediment flux characteristics, and morpho-dynamics. Channels become dynamic landscape features by virtue of the fact that the entrainment, re-entrainment, and deposition of sediments occur within them. A dynamic equilibrium occurs if entrainment and deposition occur at equal and opposite rates (Schumm, 1977; Leopold, et. al., 1964). The maintenance of the form of alluvial channels has been observed to be associated with a dominant discharge that moves the greatest amount of sediment over a graded time scale (Mackin, 1948; Wolman and Miller, 1960). However, the same dominant discharge concept does not apply to eroding rills and gullies since they are usually not stable over graded time scales of several decades or a century.

Energy inputs that drive rill erosion processes were identified by Hairshine and Rose (1992) as being derived from: a) the dissipation of energy associated with water flow within a rill, b) the raindrop energy that causes the detachment of soil particles, and c) the potential energy of the soil itself that relates to slumping of rill-sides. In the absence of gravity processes (i.e., item c), sediment flux in rills based on the excess stream power required for sediment entrainment was presented by Hairshine and Rose using equation 3. If the sediment loads generated from within the rill and the adjacent inter-rill areas exceed the transport limit, net deposition occurs. Deposition has the potential to fill a portion, or all, of the channel. When complete fill occurs, reformation of a rill channel may occur in another location on the hillslope, depending on the hydraulic conditions and sediment loading from upslope areas. A simplified rill channel sediment continuity relation based on mass is used in the Watershed Erosion Prediction Project (WEPP) model developed by the USDA to estimate hillslope sediment yields (4) (Foster, et. al., 1995).

3. $$Q_r\left(\frac{dc_i}{dx}\right)+c_i\left(\frac{dQ_r}{dx}\right)=\left[(1-H)W_b+W_s\right]\left[\frac{F(\Omega-\Omega_0)}{IJ}\right]+q_{syi}$$

where Q_r = volumetric water flow rate flow rate per rill, q_{syi} = lateral sediment flux to any rill in mass rate per unit rill length, (1-H) = unshielded fraction of the rill bottom (H = fractional shielding of the bottom of the rill provided by the deposited layer), W_b = rill width, W_s = rill wetted sidewall length, (Ω - Ω_0)= excess stream power associated with sediment mobilization, c_i = sediment concentration (c_i,=c/I, where c = total sediment concentration and I = number of sediment settling velocity classes), J = specific energy of entrainment, F = fraction of stream power used by entrainment and re-entrainment

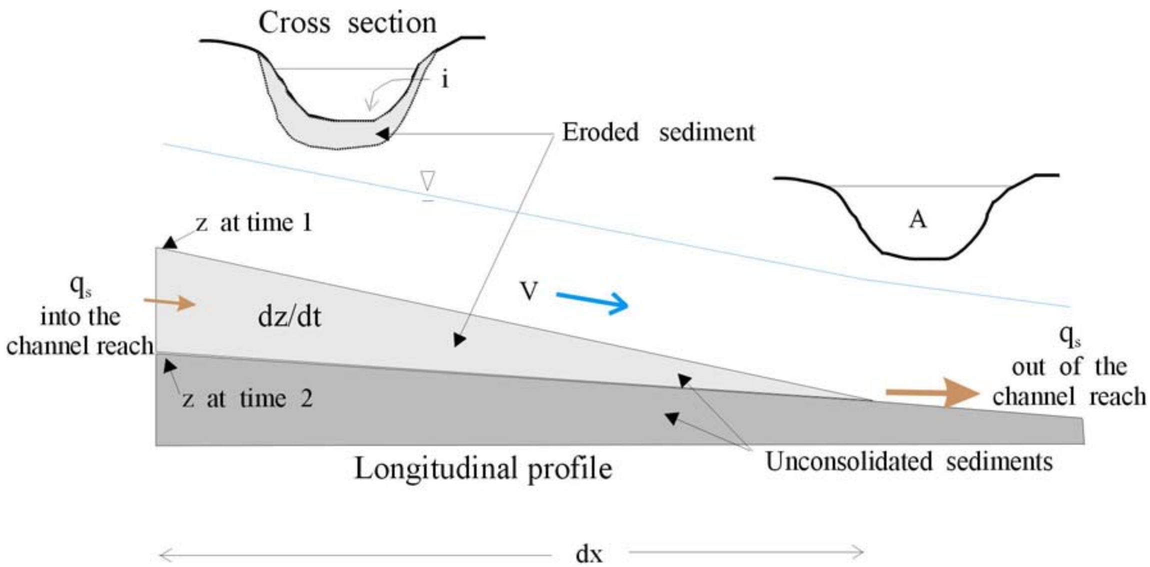
4. $$\frac{dG}{dx} = D_f + D_i$$

where G = sediment transport (kg/s/m), D_f = rill erosion rate (kg/s/m^2), D_i = inter-rill sediment delivery to the rill (kg/s/m^2)

As eroded landscape features, the dynamics of gullies have been described in terms of geomorphic thresholds that are intrinsic to the system, which includes consideration of the surrounding lithology and climate. Schumm (1977) identified the longitudinal slope as the channel characteristic capable of instigating changes through erosion processes. The results from Schumm (1977, fig. 4-14) were presented in the form of a relation between valley slope and drainage area that produced distinct populations of gullied and un-gullied channels within the dataset. However, the author cautioned that variations in vegetation cover influence erosion trends, thereby preventing recognition of a constant slope threshold relation. While the empirical slope relation was derived from channel observations in an arid climatic region, the basis for the relation can be more broadly considered since the velocity and force (or power) of the water flow in a channel is governed by slope, which then governs sediment transport. A sediment continuity equation (5) based on volume can again be used to express this relation (***fig. 6***) (Garcia, 1999).

5. $$(1-\lambda_p)\frac{dz}{dt} = \frac{dq_s}{dx} + i$$

where z = bed elevation (m), t = time (s), λ_p = soil porosity (%), q_s = sediment transport (m^2/s), x = location point on downstream axis, i = lateral sediment inputs



$$(1-\lambda_p)\ dz/dt = -dq_s/dx + i$$

q_s = sediment transport rate (m^2/s)
z = channel bed elevation (m)
x = location point along downstream axis
i = lateral sediment inputs (from channels or bank erosion)
A = flow area (m^2)
V = flow velocity (m/s)
λ_p = soil porosity (%)

Figure 6: Sediment continuity relations in an eroding stream reach. Figure source: Smith, et. al. (2003b).

Headwater channels often occur as gullies. Gully channel incision rarely progresses over time in a manner that creates a continuous profile. Instead, the profile is often discontinuous, with a series of vertical faces along its path (Leopold, et. al., 1964). The enscarpments, referred to as knickpoints, retreat in the upstream direction as headcuts that maintain the vertical face (Wolman, 1987; Whol, 2000). The lowering of the channel bed elevation and slope occurs as a result of this upstream propagation. The uppermost enscarpment is often the termination of the channel network. The disequilibrium associated with incision and head-cutting processes illustrates the importance of accurate stream channel mapping to watershed sediment flux evaluations.

5. Channel Initiation

Dietrich and Dunne (1993) pointed out that the appearance of a fluvial landscape is governed by the density and structure of the drainage network conveying water and sediment from the land. The location of the uppermost extent of the channel drainage network is one of the most critical geomorphic features to be delineated or estimated in the landscape because of its relevance to accurate channel mapping. The importance is underscored by the myriad of water resource management activities that rely on its delineation, not the least of which include the implementation of government waterways regulations associated with the federal Clean Water Act. In that instance, the complexities associated with developing consistent procedures for identifying this upper limit has led to relatively vague definitions. For example, Title 33 (Part 328) of the federal code of regulations describes the jurisdictions of “waters of the U.S.” as extending to the "ordinary high water mark", which is defined as the “line on the shore established by the fluctuations of water and indicated by physical characteristics such as clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas.” This vague definition has made the delineation of the uppermost limits of channel networks to be a highly subjective procedure.

The upper limits of drainage networks have been investigated in the context of erosion thresholds associated with channel initiation by several authors (Dietrich et. al., 1992, 1993; Istanbulluoglu, et. al., 2002; Prosser and Abernethy, 1996). The morphological feature associated with the upper limit is referred to as the channel “*head*” (Bates and Jackson, 1984). Dietrich and Dunne identified the channel head as being the upstream boundary of concentrated water flow and sediment transport between definable banks. Montgomery and Dietrich (1992) clarified that the channel head lies at a transition between unchanneled and channeled areas. They reference work by Smith and Bretherton (1972), which implied that the down-slope progression from unchanneled to channeled portions of the landscape is coincident with the transition from a convex to concave hillslope profile. The movement of channel heads as headcut formations has been documented by numerous authors as the mechanisms through which drainage networks extend through the landscape (Horton, 1945; Schumm, 1977; Montgomery and Dietrich, 1992; Abrahams, 1984). Channel heads generally have variable source areas because of their dependence on the spatial and temporal variations associated with hill-slope hydrology and erosion processes. A threshold has not been found that is capable of distinguishing hill-slopes from valleys in real, rather than modeled, landscape.

A classification system describing channel heads on the basis of incision depth and dominant runoff process was compiled by Dietrich and Dunne (1993, fig. 7.6). Types identified included *gradual*, *small steps*, *large steps*, *small head-cuts*, and *large head-cuts*. The large head-cuts were identified as being several meters in height, whereas the "gradual" transitions were characterized by a continuous longitudinal profile. The latter form exhibited evidence of concentrated sediment transport on the surface of the downstream side of the location delineated as the channel head. Interestingly, the authors attribute the dominant formation process to be associated with erosion from subsurface flows, rather than surface flows. This observation implies that the volumetric discharge associated with channel initiation is not necessary associated with rare rainfall events.

Wijdenes, et. al. (1999) also described several channel head types, including *gradual, transitional*, *rilled-abrupt*, and *abrupt* forms in a setting more consistent with Maryland's eastern Piedmont and Coastal Plain landscapes. Of these, gradual types were observed to be present in the lower and middle sections of the sloped areas, whereas abrupt types were most often found further upslope. A primary contribution from the work of Wijdenes et. al. was their consideration of factors associated with the channel head formation. They concluded that abrupt types are approaching the final stages of development. Rilled-abrupt and gradual types are potentially active, thereby acting as sediment sources. Further, they observed that some abrupt types may have been formed in association with upstream rills that have since filled with sediment.

6. A First Order Channel Definition

Despite the information provided by the aforementioned investigations and characterizations, a defensible definition of first order channel remains to be developed. The development of a definition for first order channels applicable to the entire Mid-Atlantic region would require a broad range of considerations regarding the diversity of geomorphic settings with unique geology and relief characteristics. Areas with higher relief, such as the Appalachian and Blue Ridge physiographic regions, are characterized by high drainage densities with headwater channels that are often formed from mass movements of hillslope materials, many of which occur during unusually high magnitude runoff events (***fig. 7***) (Gori and Burton, 1996). First order channels appear as debris flow scars or gullies on mountain slopes and alluvial channels are limited to lowland locations. In contrast, areas with extremely low relief, such as the Coastal Plain physiographic region on the Delmarva Peninsula, have low drainage densities.

First order channels do not have morphological characteristics that are noticeably different from higher order channels due to the low relief that prevents the dramatic dissection of the landscape into steep to moderate hill-slope gradients and gently sloped valleys. In many cases, first order channels have been artificially extended in many areas to promote drainage of the landscape (*fig. 8*).

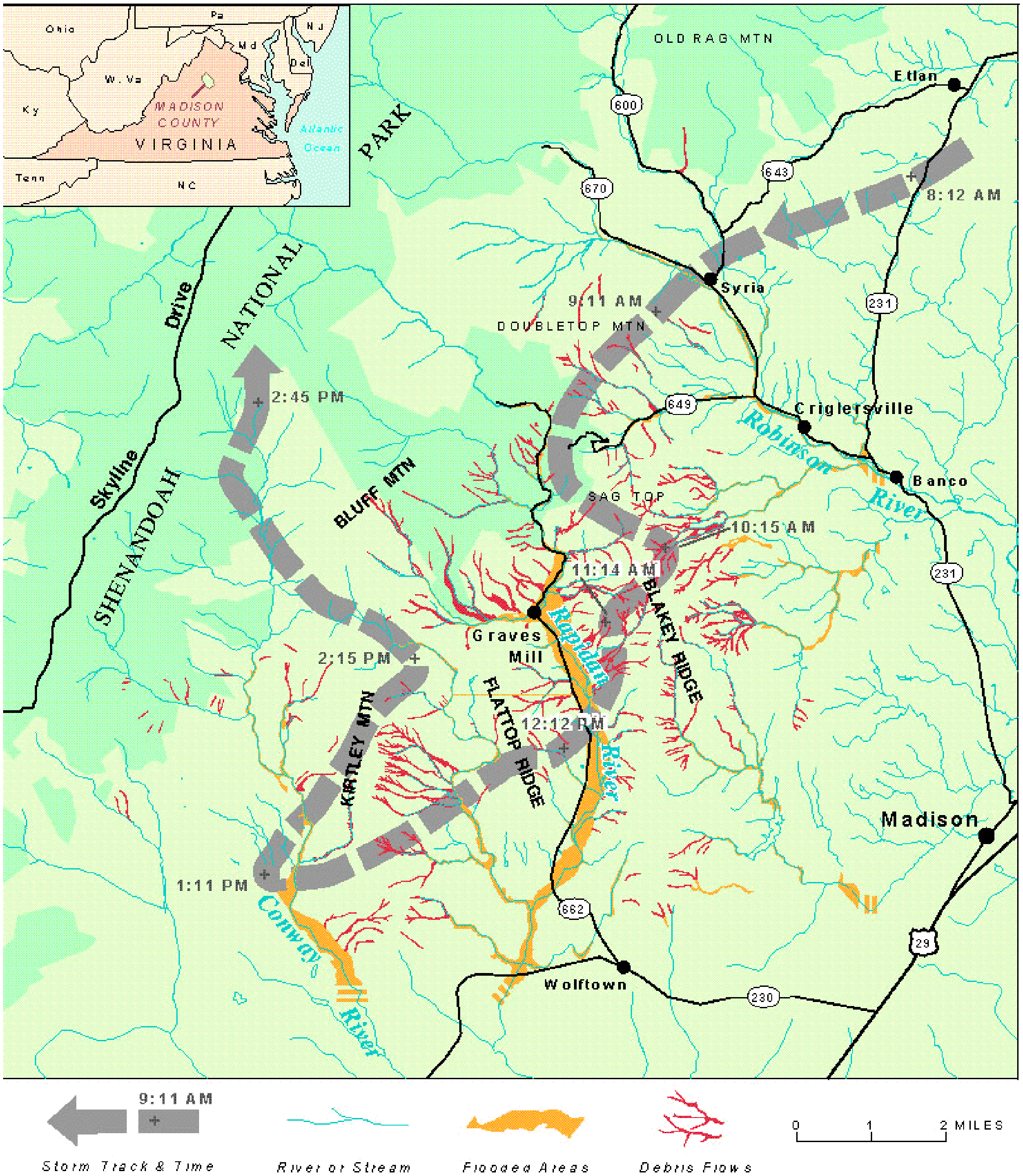


Figure 7: Map illustrating the locations of debris flows in the upper areas of the Rapidan River in the Blue Ridge mountain areas in Virginia, south of Maryland. The debris flows occurred in conjunction with an intense storm on June 27, 1995. Source: Gori and Burton, 1995. http://landslides.usgs.gov/html_files/nlic/fs159-96.pdf

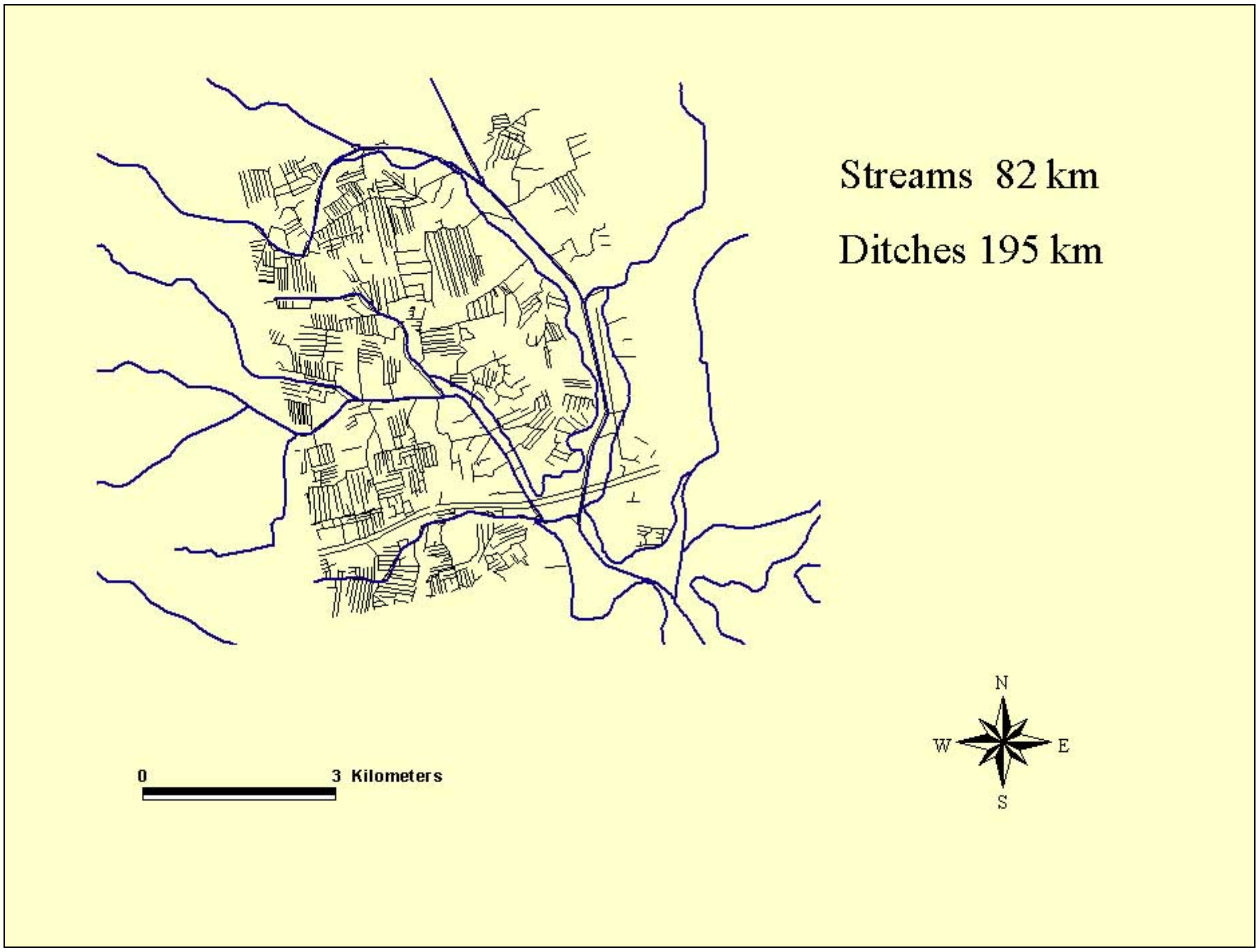


Figure 8: Drainage network map for the Upper Pocomoke River, Wicomico County, Maryland. Note extension of the drainage network through the addition of numerous ditches that now constitute first order channels. Source: MDDNR.

The Piedmont physiographic province is a well-dissected landscape that has an intermediate relief in comparison to the mountain and coastal provinces. As such, it is a useful location for the development of a baseline definition for first order channels that can be modified in more extreme settings. The channel head morphologies described by Dietrich and Dunne, as well as Wijdenes, et. al., can be found in the Piedmont even though the less abrupt types are often difficult to see due to vegetation cover. The influences of past land uses on channel head characteristics are unclear; however, historic changes in Piedmont sediment flux may influence the present slope, rates of morphological change, and related evacuation of sediment in headwater locations. In some areas, channel heads seem to be located within or near the zones of sediment storage at the base of hillslopes (Costa, 1975). The stored deposits that accumulated from sheet-wash and soil creep in low order intermittent upland stream valleys were observed by Costa to be ~1m thick and have dates of 290 ± 100 years, which corresponds with the introduction of agriculture in the Mid-Atlantic region. Overall, it's appropriate to assume that the current morphology of channel head features in the Piedmont is governed by slope and upslope sediment supply, unless direct disturbances have also occurred.

Criteria for the upper limits of based on critical flow length, l_0 (equation 2), can conceivably be developed for the Mid-Atlantic Piedmont with proper documentation of variability. Most of the land use histories in the Piedmont are similar due to the large-scale forest clearing that accompanied European colonization (Costa, 1975). Scatter in l_0 is likely due to the influence of local relief, vegetation, land use, and the history of the contributing source area. However, it may be possible to constrain the influence of landscape variables by independently considering first order channels of physiographic districts described by Reger and Cleaves (2003) that have been clustered into groups reflecting similar lithologies and relief. In particular, areas underlain by crystalline bedrock can be partitioned from those underlain by carbonate bedrock, which have different erosion characteristics.

Delineation criteria for stream channels have been presented in a number of field guides (Harrelson, et. al., 1994). The criteria have become a subject of extensive discussion in the business of stream channel assessments and rehabilitation designs, primarily because they depend on the consideration of a “bankfull stage”. The bankfull stage is associated with depositional features that can be observed in alluvial channels, which are often nested within larger channels that have their limits set by abandoned terraces (Schumm, 1977; Leopold, et. al., 1964). In contrast to these conditions, many first order channels in the Mid-Atlantic Piedmont can be broadly characterized as single gullied channels that have been formed by a dominance of erosion processes over a least a portion of their length. The magnitude of gully incision is dependent on the amount of materials eroded in conformance with equation 5 and ***fig. 6***.

Regardless of the location in either an alluvial or eroding reach, channels can broadly be defined as landscape features characterized by two banks and a bed that carry concentrated water flows. The channel banks are defined by Bates, et. al. as the “rising ground bordering a stream”. The bed is defined by the same source as “the floor of a body of water”. While these definitions provide a starting point, issues arise regarding how high a bank must be to classify the landform as a stream channel and distinguish it from a rill. Adding to the difficulty, the gradual channel head type described by Dietrich and Dunne does not appear to have banks at all.

The most complicated aspect of the first order channel definition is associated with the delineation of the upper-most boundary (i.e., the channel head). Once determined, the length of the first order channel in question extends to the point of confluence with another tributary channel, resulting in a channel of second order or higher below the confluence. In some cases, the channels will be discontinuous, even completely disappearing on the hillslope, reforming with initiation at another channel head further downslope.

Similar to delineation criteria for wetlands (Cowardin, 1979; COE, 1987), several criteria must be involved in developing criteria for delineating first order channels. The aforementioned basic channel definition, criteria for critical overland flow distances or areas, and channel head types provide a basis for the delineations. Given the variability in landscape conditions, even within a single physiographic district, the delineation must involve use of three primary criteria, including: a) delineation of a channel head, b) the presence of a channel, and c) the existence of a downstream gradient.

Channel heads can be clearly described as one of the four forms identified described by Wijdenes, et. al. (1999; fig. 2), including:

- gradual,
- transitional,
- rilled-abrupt, and
- abrupt.

Special considerations must be given to the "gradual" type that does not include measurable breaks in the hillslope profile or measurable banks on the immediate downstream side of the channel head. Dietrich and Dunne identify an area of concentrated sediment transport on the downstream side of their gradual channel head schematic. The question that needs to be resolved is whether these oblique features are maintained over extended time periods since "rills" are partly characterized by their temporary nature.

Problematic landscape features that are characterized as “gradual transitions” can potentially be delineated using several indicators. Some channels are formed and supported by deep or shallow groundwater flows. In those cases, the existence of a spring seep that meets the definition of non-tidal wetlands provided by USACOE (1987) may provide better evidence of the uppermost extent of the channel network. In the absence of a seep, the delineation of a gradual transition can be based on a “threshold” for gully channel initiation within a specific geomorphic setting. An approach for channel initiation based on the slope and area of the contributing watershed was presented by Istanbulluoglu et. al. (2002, 2004). The threshold is based on several assumptions: 1) that channels are formed when the effective shear stress of overland flow, defined by equation 6, exceeds the critical shear stress for the incipient motion of sediments on a hillslope defined by equation 7 (Vanoni, 1979), 2) that overland flow is hydraulically rough, and 3) that overland flow velocity can be represented by calculation using Manning’s equation (8) (Henderson, 1966).

6. $$\tau_f = \rho_w g h S \left(\frac{n_b}{n_a + n_b} \right)^{1.5},$$

where τ_f = effective shear stress (N/m^2), ρ_w = water density (kg/m^3), g = acceleration of gravity (m/s^2), h = flow depth (m), S = slope (m/m), n_a = roughness coefficient for vegetation, and n_b = roughness coefficient for bare soil.

7. $$\tau_c = \tau_c^* g (\rho_s - \rho_w) D_{50}$$

where τ_c = critical shear stress (N/m^2) τ_c^* = dimensionless critical shear stress (~0.043 based on Buffington and Montgomery, 1997; Istanbulluoglu, et. al., 2002), ρ_s = sediment density (kg/m^3), D_{50} = median sediment size (m).

8. $U = \frac{1}{n_t} h^{0.66} S^{0.5}$

where U = flow velocity (m/s), n_t = total roughness coefficient ($n_t = n_a + n_b$).

A deterministic model for gully channel initiation can be develop using a topography based threshold relation similar to equation 9 that is derived by equating substituting an overland flow terms into (6) and solving for area and slope (Istanbulluoglu, et. al., 2002).

9. $aS^{\alpha} > C$

where a = unit watershed area, α = ratio of discharge per unit area exponent (m) to slope exponent (n) associated with effective discharge for overland flow used in the effective shear stress computation given as equation 10, and C = ratio of effective shear stress to critical shear stress provided in equation 11.

10. $\tau = \rho_w g n_t^m q^m S^n f_s$

where q = unit discharge (m^2/s) and f_s = shear stress partitioning ratio.

11. $C = \left(\frac{\tau_c^* (\rho_s - \rho_w) d_{50}}{\rho_w g n_t^m \left(\frac{n_b}{n_t} \right)^{15}} \right)^{\frac{1}{m}} \left(\frac{1}{r} \right)$

where r = net water input rate (m/yr).

While the runoff criteria need field-testing, evaluation, and refinement, they are based on the consideration of several important factors and assumptions, including:

1) Hillsides in the Piedmont evaluation using USGS 30-meter grid elevation data have moderate slopes averaging 0.074 m/m, with a standard deviation of 0.056 m/m (M. Herrmann, MDDNR, unpublished data).
2) Recent observations indicate that gravel-sized sediments in shallow confined flow areas are mobilized during rainfall runoff events that occur with a frequency less than 5 years (S. Smith, MDDNR, unpublished data).
3) Gully-channel initiation in Maryland's Piedmont is dominated by erosion from overland flow.
4) For a true gully to form, runoff events capable of moving sediment materials must occur frequently enough to maintain a permanent channel hill-slope feature.
5) Runoff rates (not volumes) are important determinants of gully-channel formation, thereby making it problematic to use simplified 24-hour rainfall frequency information (USDA, 1986) for the analysis.

Use of a threshold criterion (equation 9) requires consideration of the variability in slope conditions, sediment grain sizes, rainfall characteristics, and roughness. Limiting evaluations to a single landscape setting constrains the variability in slope conditions, sediment grain sizes, and rainfall characteristics. Accordingly, contributing watershed areas (introduced via the *a* term in equation 9) may be reasonably consistent for a specified land use condition and vegetation roughness may be an important determinant of variations in the threshold values. Both water input rates and surface roughness may vary seasonally, also affecting the threshold criteria.

Given the flow depth considerations associated with the force driving erosion processes (equations 6 and 10), the locations that are likely to experience erosion at magnitudes and frequencies large enough to cause permanent gully-channel initiation are likely to be commensurate with locations of shallow confined flow. Roughness changes through vegetation development are important for water flow shear stress computations (Gwynn and Ree, 1980). Upslope sediment supply also must be considered in the evaluation of channel formation and maintenance, as suggested by the sediment continuity relations (equations 4 and 5) (Flanagan and Nearing, 1995).

7. Topology Modeling

Evidence from the work by Horton and the more recent summary by Montgomery and Dietrich indicate that landscape attributes associated with drainage networks are scale-dependent. The determination of critical flow length and contributing area relations associated with channel initiation requires high quality representations by photographs, topographic maps, and/or elevation data. Mapping scale has been found to affect the outcome of drainage network mapping exercises using aerial photos and topographic maps at scales ranging from 1:12,000 to 1:62,500 (Miller, et. al., 1999). In a 142 km^2 basin, Miller et. al. observed that the number of delineated first order channels ranged from 6,286 using 1:12,000 aerial photograph data to 74 using 1:62,500 topographic maps. Their effort concluded that the "noise" generated by small watershed variability is removed in analyses performed using small-scale topographic data. The loss of this variability alters the watershed and drainage network delineations, thereby supporting the need for detailed attention to the mapping and collection of data on smaller watersheds. Other problems associated with the use of loosely established definitions of stream heads on topographical maps also lead to drainage network mapping inaccuracies (Nakayama, 1997). Blue lines drawn on maps without supporting evidence, suing the points of bends in contour lines, and locations where valley widths exceed valley lengths are examples of such manually derived delineation criteria that have unquantified errors.

Advancements in computer processing capabilities have opened new opportunities for morphometric mapping using digitized elevation information. An evaluation of the effects of elevation data on the accuracy of digital elevation models was conducted by Walker and Willgoose (1999) with attention to hydrologic and geomorphic applications. Their analyses using field-verified photogrammetry and digital elevation models indicated that the source of the elevation data was of greater importance than grid spacings <25 meters for the development of accurate drainage network and watershed boundary maps. They cite work by Gyasi-Agyei et. al. (1995) that established the relation given by equation 12 to determine DEM adequacy for the extraction of stream networks. Adequacy is confirmed if the ratio of the average pixel drop to the vertical resolution given in the left side of the relation is greater than unity. The maximum horizontal resolution for which details are reliable for the development of drainage network maps was similarly established using equation 13, with the DEM being unreliable when D_x is less than the term right side of the equation (Gyasi-Agyei, et. al., 1995). Watershed width functions and cumulative drainage area relations were poorly estimated using published photogrammetric and topographic map data. The inability to accurately develop drainage area functions can be particularly problematic because of the associations between a critical overland flow length and/or factors related to saturation overland flow.

12. $\frac{\bar{S}D_x}{\sigma_{\Delta Z}} > 1$

where D_x = horizontal resolution, $\sigma_{\Delta Z}$ = standard deviation of the relative error in elevation, and $\bar{S}$ = mean slope.

13. $D_x > \frac{\sigma_{\Delta Z}}{\bar{S}}$

8. Proposal: Piedmont Drainage Network Mapping

Most USGS digital mapping products used in Maryland are primarily developed from existing topographic maps (USGS, no date). Special features, including streams, are traced or scanned from the hand-rendered maps. In recent years, local and state government agencies have expanded a variety of mapping layers to meet the demands for geographic information systems used in environmental and land planning activities. Expansion of the USGS blue-line streams has been accomplished primarily with the use of existing USGS topographic maps and aerial ortho-photography, without ground-truthing. As a result, many headwater streams in Maryland remain unmapped (Weber, 2003).

An enhanced stream layer that expands the documentation of the existing channel network in Maryland is in high demand for habitat conservation, water quality assessments, and land planning efforts. Mapping technologies that use high-resolution photogrammetry and Light Detection and Ranging (LIDAR) technologies are significantly improving the ability to identify intricate geomorphic features, such as headwater channels, by sensing small changes in elevation (Miller, 2004). The LIDAR data being acquired in large portions of the state are used for the production of 2-foot contour topographic maps. While the development of elevation data with resolution smaller than 2 feet is technically possible, it is currently not cost efficient. The 2-foot contour limitation combined with the heterogeneity at the upper-most ends of drainage networks requires that criteria be created to guide the production of new stream maps. Regardless of the approach, the mapping should be conducted to provide for some accountability of uncertainty in the location of channel heads.

A pilot project is proposed to develop an approach for enhanced stream mapping in Maryland's Piedmont as an effort to meet contemporary stream mapping demands, optimize use of new elevation data acquisition efforts, and implement standards that can be efficiently implemented across large areas. The location proposed for the pilot study is the Cattail Creek watershed in Howard County, Maryland (***fig. 9***). This watershed was selected for several reasons. It is located in the Upper Patuxent River watershed, which coincides with an ongoing sediment budgeting project that could benefit from enhanced drainage network maps. The watershed is limited to two delineated geomorphic settings, the Hampstead Uplands and Glenwood Uplands physiographic districts (Reger and Cleaves, 2003), that have similar lithologies and landscape histories. There is also an abundance of digitized spatial data available for the watershed, including existing USGS maps, historic aerial photographs, and three sets of elevation data that can be used to develop digital elevation models (DEMs) (Table 1).

Source Data	Map Scale	Vertical Accuracy	Horizontal Accuracy	DEM Cell Size
LIDAR	1:2,400	0.185 cm	2 m	2 m
Photogrammetric 1.5m elevation contours	1:2,400	0.75 m	2 m	5 m
National Elevation Dataset 7.5 minute quad maps 6 m elevation contours	1:24,000	5 m	12 m	30 m

Table 1. Data Sources, Scale, and Accuracy.

The USGS DEM releases data accuracy estimates with the National Elevation Dataset. The Woodbine Quadrangle, where Cattail Creek is located, has a nominal vertical accuracy of 5 meters. The methods for USGS DEM creation are well documented (USGS, 1999b and USGS, 1998). The DEM developed from photogrammetry is documented in the product's metadata. Analytical triangulation and ground surveys were used by Vargis, LLC to delineate contours of the terrain for Howard County using the photogrammatric data. The "Topogrid" routine developed by the Environmental Systems Research Institute (ESRI) was utilized to convert the contours to a DEM. This routine is run in ArcInfo and uses elevation contours and survey points to generate a DEM using an iterative interpolation process (ESRI, 2001). Elevation accuracy from the LIDAR data acquisition is estimated to have a RMSE value for vertical accuracy of 18.5 cm (Miller, 2004).

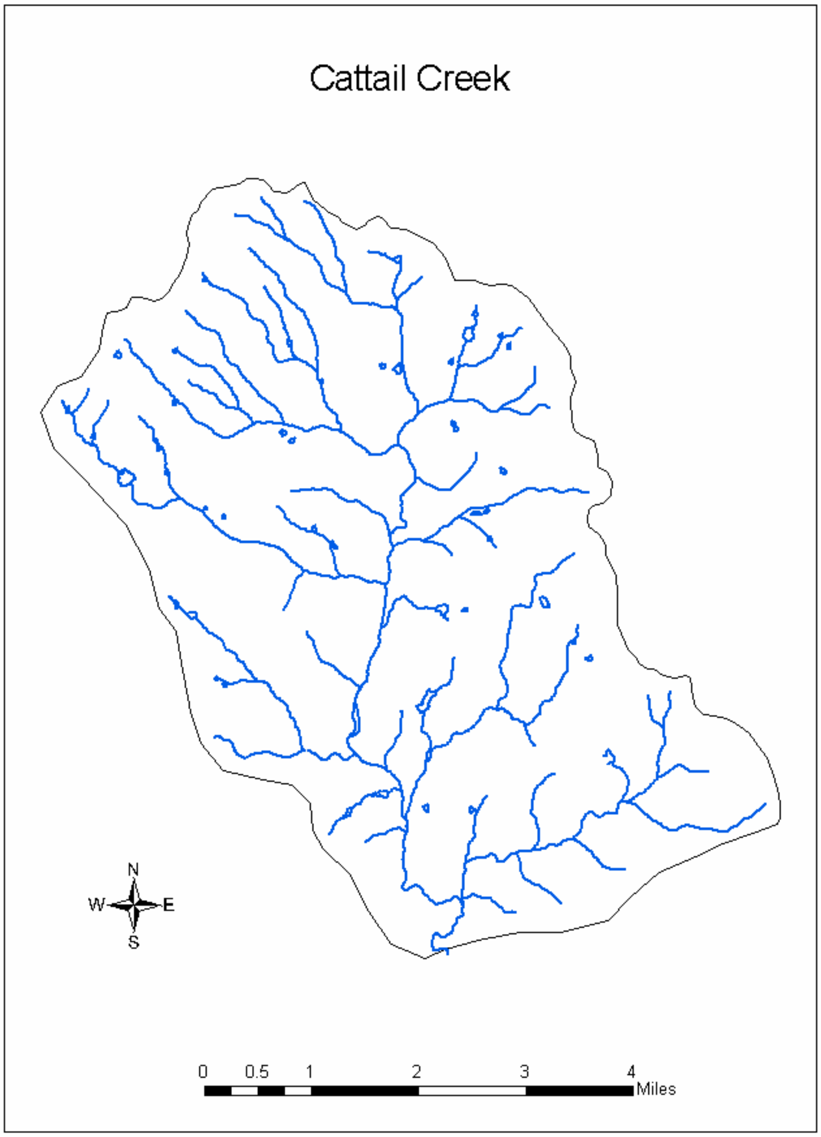


Figure 9: Cattail Creek watershed and blue-line drainage network, Howard County, Maryland.

The DEM data will be processed to conduct topological analyses using topographic and river network analysis software (Research Systems, Inc., 2001). The software creates a flow grid from the DEM in which all depressions are filled (see Fairfield and Leymarie, 1991). A drainage network is then generated that drains every raster grid space produced from the DEM (***fig. 10***). From this network, rules can be developed based on drainage area to trim the upper lengths of the drainage network to simulate the extent of permanent channels in the landscape (***fig. 11***).

The trimmed networks can then be evaluated relative to field-verified channel head locations. Delineations of the channel head in the field can be made using the first order channel definitions described in the previous sections. The locations of the actual channel heads can be documented using high-resolution global position system receivers.

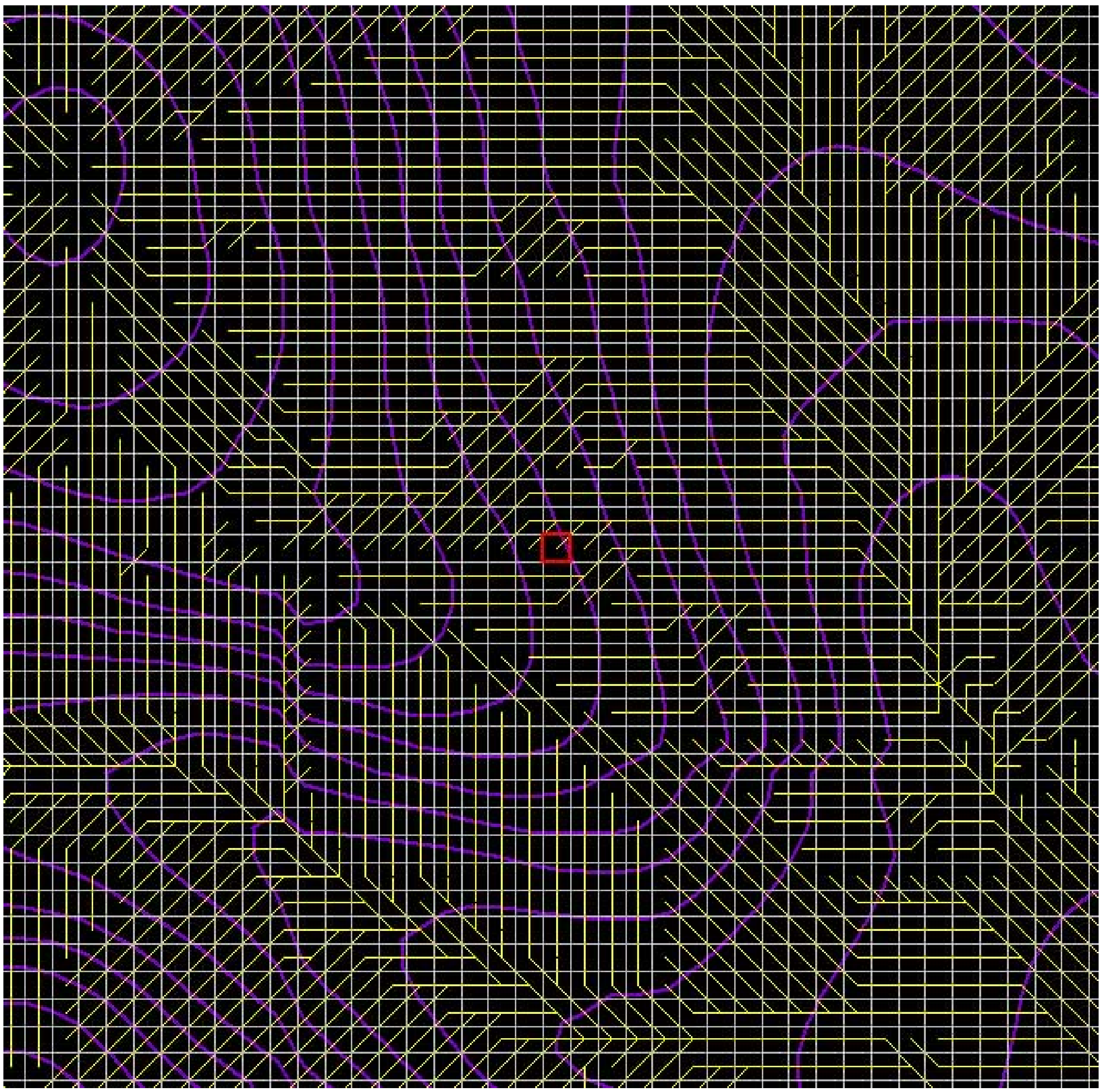


Figure 10: Flow grid constructed for the Cattail Creek watershed using the DEM created from the photogrammetry-derived 5-foot contour data. White lines are 5-meter grid spaces, purple lines are interpolated contour lines, and yellow lines are the flow paths that established the untrimmed drainage network.

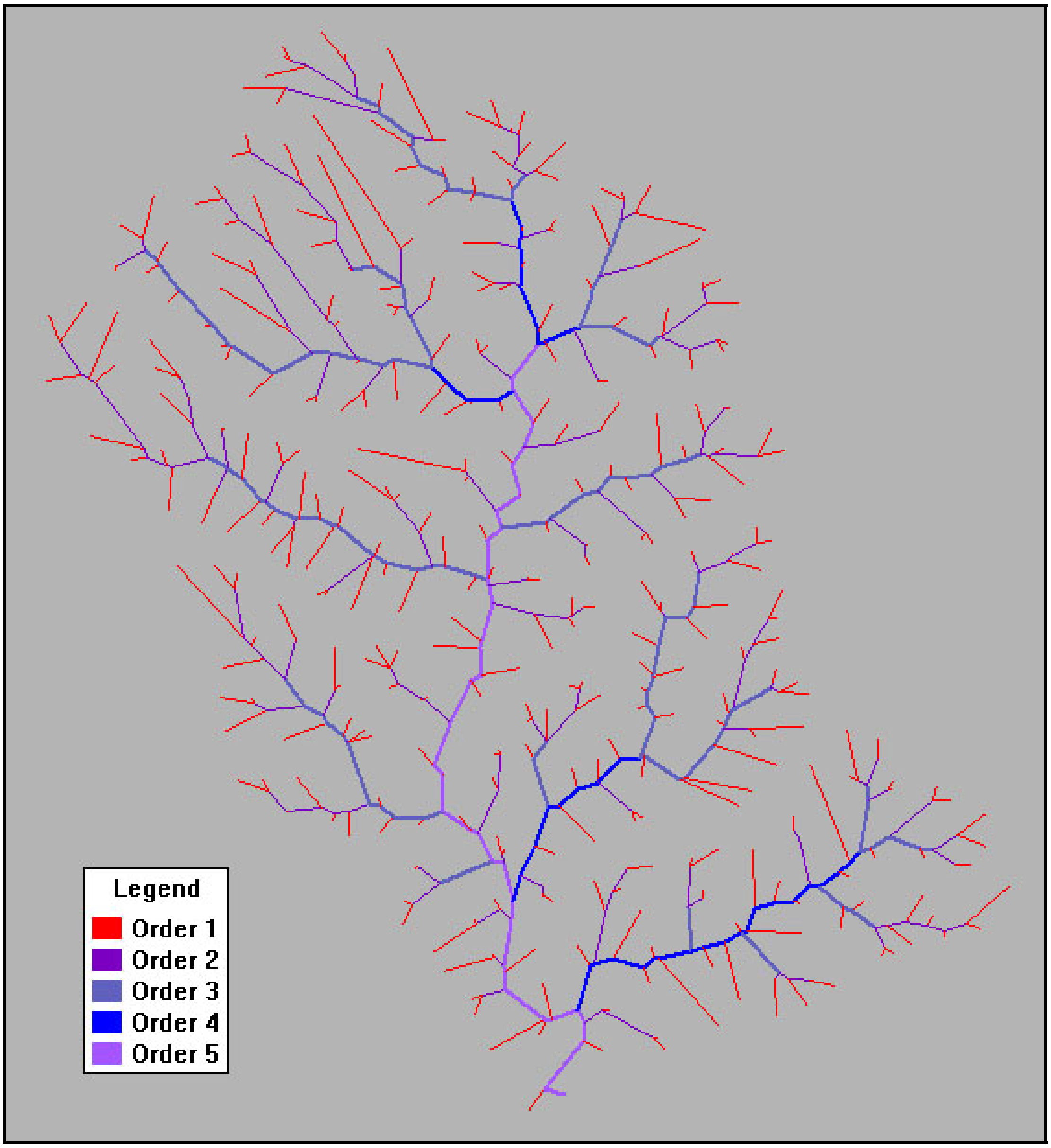


Figure 11: Cattail Creek drainage network developed by trimming the drainage network shown in Figure 10 using a channel head source area criteria of 0.05 km^2.

The contributing drainage area criteria for the upper limit of the channel network that has the highest level of correlation with the field-verified channel head locations will be used for the development of a new channel network map for Cattail Creek. Results from evaluations of drainage networks developed from each of the DEMs under consideration can be presented as total stream lengths, stream lengths for each channel order, drainage density, bifurcations ratios, and average channel relief for each order. Uncertainty in the accuracy of the synthetic drainage networks can be calculated relative to the partial uncertainties associated with the DEM data, sizes of the channel head source areas, and channel head locations (Taylor, 1997). Morphometric data can be compared for the networks developed from the three DEM data sources and the original blue-line stream maps extracted from USGS 7.5' quadrangle maps. Where determined to be present, "gradual" head cut formations can be measured and evaluated relative to the criteria described in the previous section.

9. Summary

Previous work on stream channels has indicated that channel network properties have associations with critical overland flow path lengths and channel headward growth characteristics, both of which have relations with lithology, climate, and watershed land cover. Approaches for the analysis of the morphometry of drainage networks were outlined by previous studies. Classification systems to describe the morphology of the uppermost channel limits have been presented by several authors. Information from these efforts can be used in conjunction with modern computer processing advancements to develop improved stream channel maps in Maryland. The maps can be developed using approaches that allow for the quantification of uncertainty (i.e., error), thereby enhancing their use in subsequent studies of sediment flux that rely on estimates of the network channel lengths. Given it's intermediate relief, landscape history, and abundance of spatial data, the Piedmont physiographic province is a good location to develop baseline criteria for defining first order channels and improving methods for drainage network delineations. Accordingly, a pilot study has been proposed in the Cattail Creek watershed of Howard County. The study focuses the development of synthetic drainage network maps using three DEMs derived from three different sets of source elevation data. The synthetic maps generated from the DEMs can be evaluated relative to field verified stream channel data and existing USGS blue line channel delineations. Uncertainties associated with the resulting network delineations can be calculated for each DEM under consideration. Channel head delineation criteria can be assessed using morphological classification criteria and threshold parameters associated with surface slope and contributing drainage area. The results can collectively be used to make recommendations to guide approaches to stream network delineations and the selection of criteria in other watersheds and physiographic settings in the state.

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